Consequences of Accidental Beam Loss in the NuMI Primary Beam Line

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1 Introduction

A fraction or, in the worst case, a full 120-GeV proton beam could be lost at many locations along the NuMI primary beam line. A high intensity fast spill of a small size beam hitting the beam pipe can result in its failure as it has happened with the NC1D1-1 vacuum tube, where a video scan showed a hole along the tube wall [1]. The failure was due to a rapid temperature buildup of several beam pulses at a 2 Hz repetition rate. Below we analyze an instantaneous temperature rise of the NuMI beam pipe at a single quasi-local loss of a full 120-GeV proton beam for two cases which are considered representative ones with results which are thought to be rather generic. A detailed simulation with the MARS14 code [2] has been performed to estimate consequences of such an event. Two beam loss scenarios are considered: a proton beam hits the NuMI beam pipe at a grazing angle and the beam hits a center of the pipe wall at a zero angle at an aperture transition.

2 Grazing Incidence

A direct hit on the beam pipe in the NuMI primary beam line can be caused by a deviation from the nominal beam trajectory, generating a wrong beam angle θ. Typically, impact angles of up to about 1.5 mradians are what an irradiated beampipe sees. Impact angles greater than a few mradians are much less probable, except for the special case of normal incidence discussed below. A possible scenario for such a significant beam accident is an offset beam impacting on the beam pipe of an EPB dipole. The MARS14 calculational model is shown in Fig. 1. The pipe itself has approximate dimensions 1.5 inches (across the gap) by 3.5 inches, or 3.81$\times$8.89 cm, with the ellipse curvature radius at the point P of $R_c = 1.745^2/4.286 = 0.71$ cm. Material is type 304 stainless steel, with a wall thickness of 0.0625 inches, or 0.159 cm. The beam line description and beam parameters were provided by Peter Lucas [3] for the NuMI baseline intensity of 4×10^{13} protons per pulse. The beam is assumed to be a Gaussian with σ_v=σ_x = 0.15 cm and σ_h=σ_y = 0.099 cm. The beam axis path in the pipe wall is at 333 <z<439 cm.

A 3-D temperature field is calculated in MARS14 from energy deposition density in hadronic-electromagnetic cascades and a temperature-dependent heat capacity $C(T)$ for the 304 stainless steel, using T_0=27°C as the initial temperature. In the worst case the beam hits the pipe in a vertical plane (minimal R_c) which corresponds to the maximum temperature rise (see below). Results, averaged over the pipe thickness, are presented as a function of a l longitudinal coordinate along the z-axis and a s azimuthal coordinate along the pipe circumference.

Fig. 2 shows an example of calculated instantaneous temperature distribution in the NuMI beam pipe after a single pulse for θ=1.5 mrad. The maximum instantaneous temperature in this case is 408°C. Longitudinal and azimuthal temperature profiles are presented in Fig. 3.

Maximum instantaneous temperature in the baseline beampipe is shown in Fig. 4 as a function of a grazing angle θ. The distribution reaches its maximum of 1060°C for a single pulse at about 12 mrad and then slowly drops. It is interesting that if the beam hits the same elliptical pipe in a horizontal plane, the temperature rise is lower. Fig. 5 shows how maximum temperature drops with the ellipse curvature radius R_c at the point P. A picture on the right explains the effect. An ellipse with the center at point O shows the beam area. As can be seen, based on comparison of arc distances l_1 and l_2 , the surface with greater curvature S_2 has larger irradiated area as compared with the surface S_1 of lower curvature. Therefore, the total number of protons impinging onto the beam pipe is greater for S_2 than for S_1. For Gaussian-like distributions the effect is even stronger because of a $|Oa| \leq |Ob|$ condition.

3 Normal Incidence

At a transition from a larger aperture pipe to a smaller one a beam can hit the pipe at a zero angle with its center coinciding with the center of the beam pipe wall in a transverse direction. Fig. 6 shows longitudinal distribution of energy deposition and temperature in the beam pipe in such a case. An instantaneous temperature is calculated again for a single pulse of 4×10^{13} 120-GeV protons at T_0=27°C. One can see that at shower maximum (∼13 cm, slightly less than one interaction length in steel), temperature reaches about 1000°C, only slightly less than the absolute peak at θ=12 mrad in the grazing angle irradiation case.

4 Beam Pipe Failure

In both cases considered, the maximum instantaneous temperature can reach about 1000°C for a single pulse of 4×10^{13} 120-GeV protons. Although this is lower than the stainless steel melting point of 1535°C, and may look acceptable for a one-shoot beam accident, sequent beam loss pulses at the same location will result in temperature build-up and the pipe melting after several pulses. Extrapolation of the ANSYS results of Ref. [1] to the grazing angle situation considered, shows that temperature buildup may result in the beam pipe melting after about four-five sequent pulses lost at the same location. If the incident angle θ is larger than about 5 mrad or it is a normal incidence, then a second sequent pulse lost exactly at the same location is prohibited. Moreover, the stainless steel strength drops rapidly with temperature (Fig. 7 taken from Ref. [1]), reaching 50% of its original value at about 500$^{\circ}C$. This makes the situation even more severe.

5 Conclusion

There is no problem with a loss of a single beam pulse in the NuMI primary beam line at an assumed baseline grazing angle of about 1.5 mrad. The maximum instantaneous temperature is 408$^{\circ}C$. In the worst cases of normal incidence or a hitting angle of $\sim$12 mrad, the beampipe does not reach melting temperature for a single pulse of 4×10^{13} protons, but loses however almost 85% of its strength. A detailed ANSYS analysis would certainly help understand this case better. For all circumstances, full beam loss of several pulses sequently exactly at the same location should be excluded.

References

[1] Anthony Malensek, "Beampipe Failure of NC1D1-1", Fermilab, December 12, 1996.

[2] N. V. Mokhov, "The MARS Code System Users Guide, Version 13(95)", Fermilab-FN-628 (1995); N. V. Mokhov, O. E. Krivosheev, "MARS Code Status", *Proc. Monte Carlo 2000 Conference*, Lisbon, October 2000, Springer, 943-948; also Fermilab-Conf-00/181 (2000); http://www-ap.fnal.gov/MARS/.

[3] Peter Lucas, private communication, December 2001.

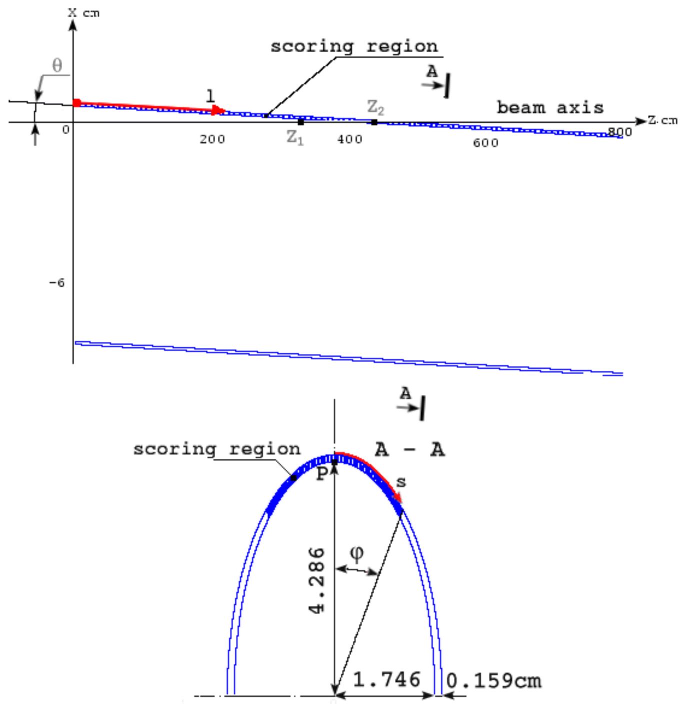

Figure 1: NuMI beam, beam pipe and scoring regions as described in MARS14.

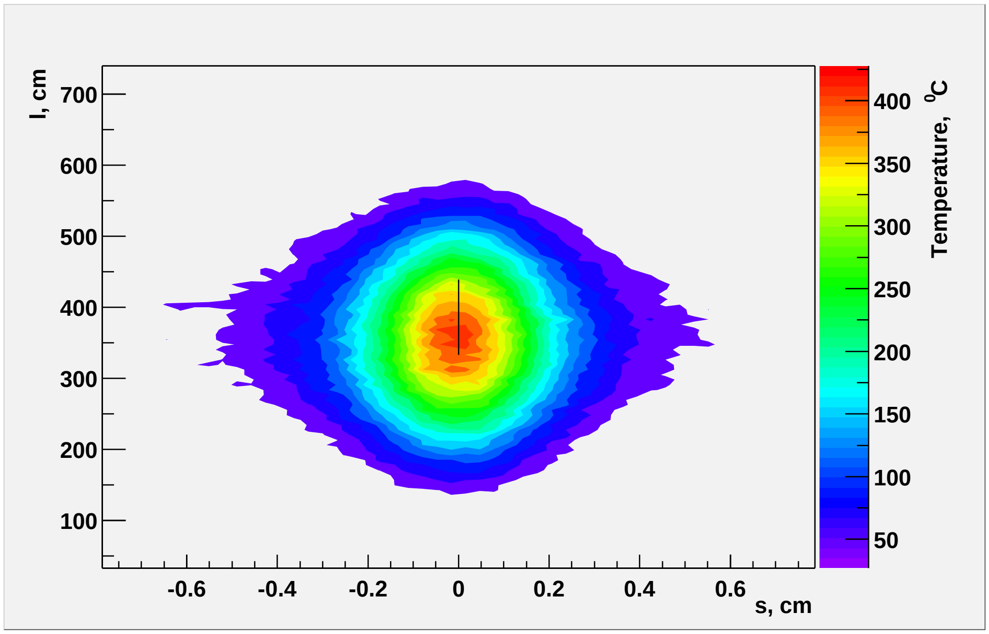

Figure 2: Instantaneous temperature distribution in the NuMI beam pipe. A vertical line corresponds to the beam axis path in the pipe. T_0=27°C, θ=1.5 mrad.

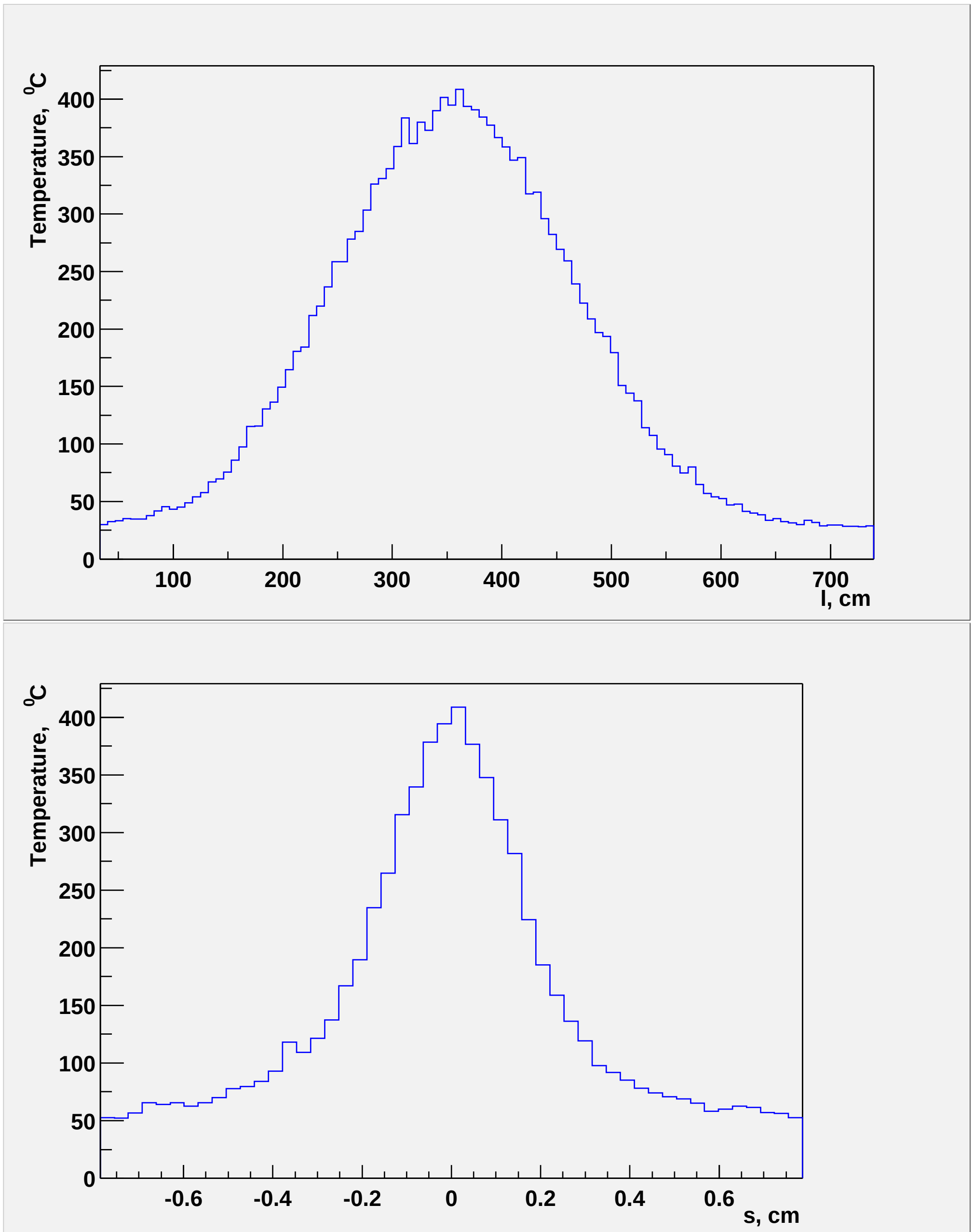

Figure 3: Longitudinal (top) and azimuthal (bottom) instantaneous temperature profiles in the NuMI beam pipe for a single pulse of $4{\times}10^{13}$ 120-GeV protons. T_0=27$^\circ C$, θ=1.5 mrad.

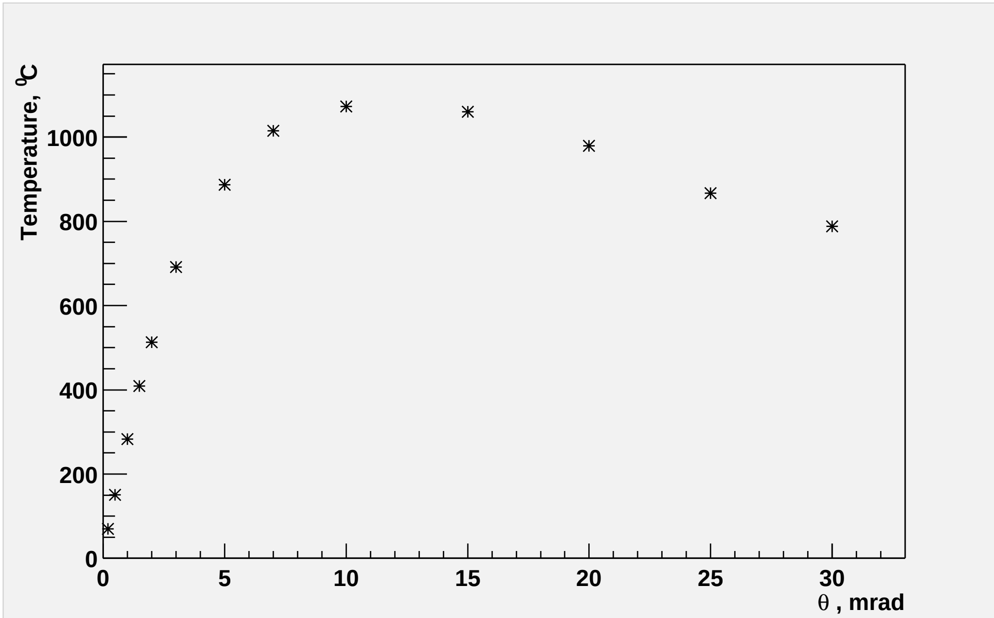

Figure 4: Maximum instantaneous temperature in a baseline case *vs* incident angle θ for a single pulse of 4×10^{13} 120-GeV protons. T_0=27$^{\circ}C$.

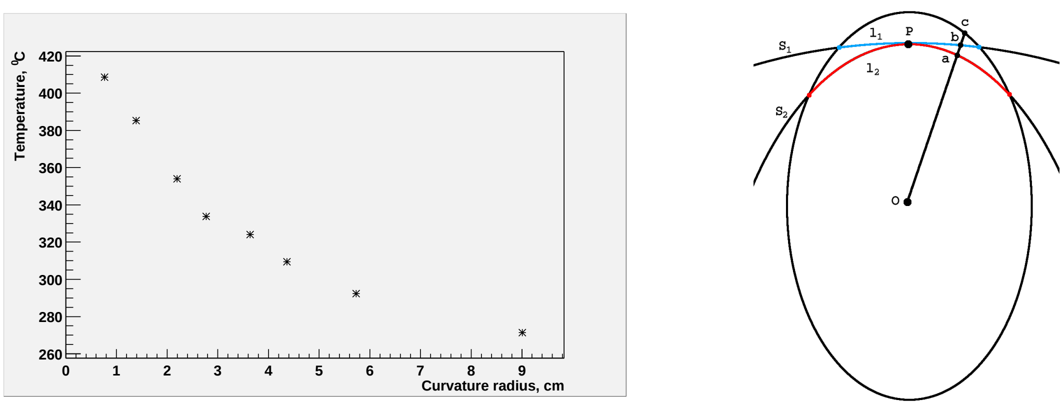

Figure 5: Maximum instantaneous temperature at θ=1.5 mrad *vs* beam pipe curvature radius at the hitting point for a single pulse of 4×10^{13} 120-GeV protons at T_0=27$^{\circ}C$ (left) and corresponding geometry (right).

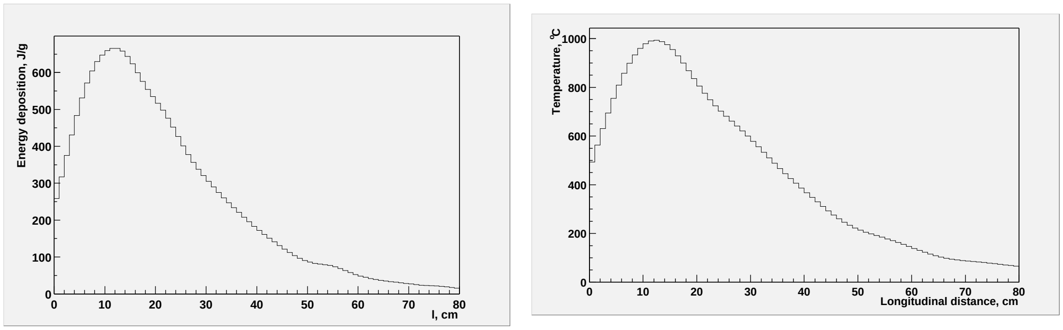

Figure 6: Energy deposition (left) and instantaneous temperature (right) distributions along the NuMI beam pipe at normal incidence for a single pulse of 4×10^{13} 120-GeV protons.

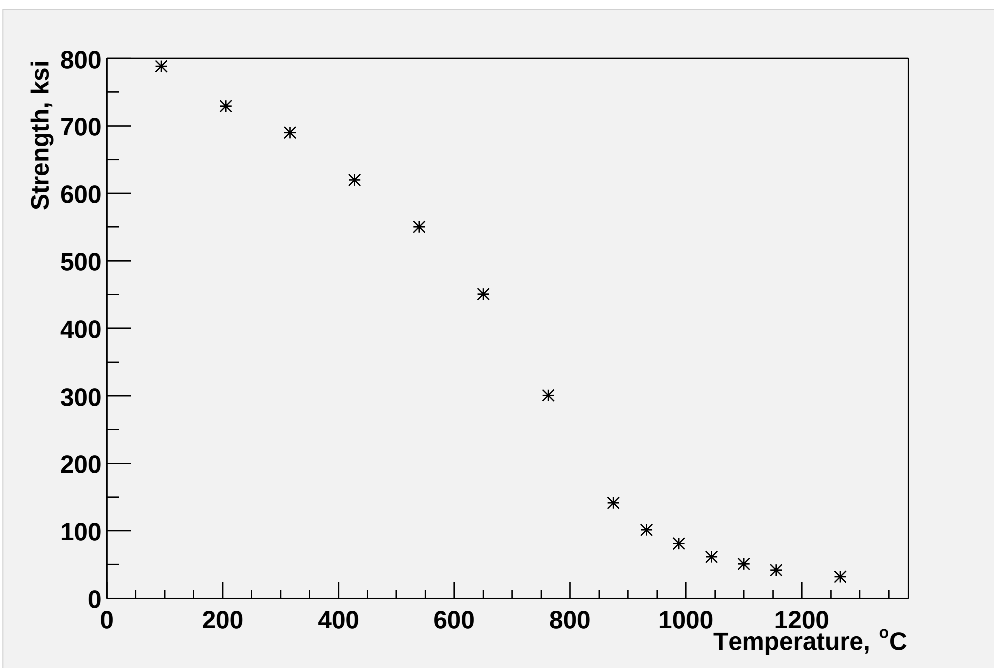

Figure 7: Ultimate tensile strength of stainless steel (type 304) *v*s temperature.